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A comparative review on the specific heat of nanofluids for energy perspective

I.M. Shahrul*, I.M. Mahbubul, S.S. Khaleduzzaman, R. Saidur*, M.F.M. Sabri

Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

Nanofluid is one of the novel inventions of science. Nanofluid can be used for energy savings by increasing the heat transfer performance of the heat recovery systems, which are generally struggling to overcome the present challenging issues such as global warming, greenhouse effect, climate change, and fuel crisis. Specific heat capacity is necessary to analyze energy and exergy performances. This paper extant different characteristic of specific heat capacity of nanofluids containing preparation and measuring methods, effects of volume fraction, temperature, types and sizes of nanoparticles and base fluids. Additionally a compilation has been done on available theoretical correlation related to specific heat of nanofluid. Based on existing experimental and theoretical results, nanofluid specific heat falls with the enhancement of volume concentration of nanoparticle though there are some inconsistencies among outcomes. Moreover, specific heat of the nanofluids are generally increased after adding dispersant in the mixtures. However, many contradictory results about the effects of temperatures on specific heat of nanofluids found in the literatures. Therefore, this review will help the researchers and related peoples to get enough information to select a nanofluid based on specific heat for their practical applications.

Contents

1. Introduction

Nanofluids are now of great interest for improving heat transfer performance that are related to energy savings. Many researches have been done to investigate different properties of nanofluids.

* Corresponding authors. Tel.: +603 7967 7611; fax: +603 7967 5317.
E-mail addresses: shahrul_ipe@yahoo.com, shahrul.ipe@gmail.com (I.M. Shahrul), saidur@um.edu.my (R. Saidur).

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Most of the researchers gave more attention to thermal conductivity of the nanofluids. Some other emphasized the viscosity of nanofluid. However, specific heat (C_p) is also very important characteristics of nanofluids. To analyze energy and exergy, specific heat of nanofluid is most demandable properties. For example Saidur et al. [1], Leong et al. [2] and Sundar and Singh [3] showed the following Eqs. (1)–(3) respectively, where the calculation of energy effectiveness, measurement of heat recovery and dimensionless parameter of heat transfer are depend on specific heat.

$$Q_r = m_{fg} \times C_p \times \Delta T_{fg} \tag{1}$$

$$\varepsilon = 1 - \exp\left[\left(\frac{1}{C^*}\right)(NTU)^{0.22}\left\{\exp\left[-C^*(NTU)^{0.78}\right] - 1\right\}\right] \tag{2}$$

where,

$$C^* = \frac{C_{\min}}{C_{\max}}$$

And assumed, $C_{\min} = (\dot{m}C_p)_{nf}$ and $C_{\max} = (\dot{m}C_p)_{bf}$

$$Nu_{nf} = f\left(Re, Pr, \frac{k_p}{k_{nf}}, \frac{(\rho C_p)_p}{(\rho C_p)_{bf}}, \ \phi, \ \text{particle size and shape}, \ \text{flow structure}\right) \tag{3}$$

Nanofluids are prepared by dispersing nanometer-sized particles, generally less than 100 nm, in a base fluid such as water, ethylene glycol, propylene glycol, oil and other conventional heat transfer fluids. Choi [4] from Argonne National Laboratory (US) first invented this fluid in 1995 and since then research is going on tremendously. Addition of high thermal conductivity metallic/non-metallic nanoparticles into the base fluid increases the thermal conductivity of such mixtures, thus enhancing their overall heat transfer capability. In the past decade and half, there have been abundant experimental as well as numerical studies done to explore the advantages of nanofluids under wide variety of conditions [5,6].

Recently, lot of research has been done about nanofluids, but most of them are related to the heat transfer [7–16], pressure drop [17,18], and energy [19,20] analysis. However, the above performance parameters are depends on the fundamental properties like: thermal conductivity, viscosity, density, and specific heat capacity [21]. There are a lot of studies available about thermal conductivity [22–35] and viscosity [36–38] of nanofluids. Studies on the specific heat of nanofluids have acknowledged very poor consideration. As a matter of fact, to evaluate the thermal performance of nanofluids it is essential to determine the specific heat accurately. For example, specific heat necessary in the measurements of the thermal conductivity [39], thermal diffusivity [40,41] and spatial temperature inside the flow [42]. In natural convection, it is one of the key factors for telling the nanofluids and the convective flow position [39,43].

Very few research studies available on specific heat of nanofluids and Sekhar and Sharma [44] mentioned that, more studies on temperature-dependent specific heat capacity over a wide range of nanoparticle size and concentration combinations have to be conducted to get the results. For the first time, Pak and Cho [45] investigate the specific heat of nanofluid. They found that specific heat is decreased with the increase of particles volume concentrations in the water. Similarly, Zhou and Ni [43] observed that, the nanofluids specific heat decreased with the increase of nanoparticle volume fraction. Their correlation is in worthy promise with the expectation of the thermal equilibrium model, which is first used by Xuan and Roetzel [46]; while the further simple mixing model fails to forecast the specific heat of nanofluids [45]. Vajjha and Das [47] measured the specific heat of three nanofluids containing Al_2O_3, ZnO and SiO_2 nanoparticles. The first two are dispersed in a base fluid (60:40 mixture of EG/W) and the last one in deionized water. They also found that the specific heat decreases with the increase of volumetric concentration of nanoparticles but the specific heat of those nanofluids increases with the increase of temperature. Robertis et al. [48] did experiments with Cu–EG nanofluid and found that the specific heat of that nanofluid decreased for nanoparticles suspension in the base fluid and it increased with the increase of temperature. Elias et al. [49] reported similar trend of results as the specific heat of the nanofluids was decreased with the increase of volume concentration and it was increased linearly with the increase of temperature. Where they experimentally investigated the specific heat capacity of Radiator Coolant (RC) based nanofluid with 0 to 1 vol% of Al_2O_3 nanoparticles and different temperature from 10 to 50 °C. However, Saeedinia et al. [50,51] observed the opposite trend as the specific heat for the suspension of CuO nanoparticles in Pure Engine Oil (PEO) decreasing with the increase of temperatures but they found specific heat of that nanofluids decreasing with the increase of volume concentrations. Similarly, Shin and Banerjee [52] reported that the specific heat capacity of alkali metal chloride salt eutectics doped with SiO_2 nanoparticles enhanced by 14.5% at 1% mass concentration of SiO_2 and it is decreasing with the increase of temperature. Pakdaman et al. [53] doped Multi walled carbon nanotube (MWCNT) (diameter 5–20 nm) in pure Heat Transfer Oil (HTO) and observed that specific heat capacity reduction of the fluid, when nanoparticles are scattering in base fluid and it was increased with the increase of temperature. An exhaustive list has been summarized in Table 1 about the available literature on effect of volume concentration and temperature on specific heat of nanofluids.

Instance of specific heat, almost all literature carry on volume concentration and temperature effect. In case of thermal conductivity, viscosity and density of nanofluids, they increase with the increase of volume concentrations. Regarding the specific heat capacity of nanofluid there are contradictions for both the effect of volume concentrations and temperatures. Though, there are very limited literatures about specific heat capacity of nanofluids and the results are contradictory. It is very difficult for the researchers and scientists to get enough idea about specific heat of nanofluid from one or two papers. Therefore, it is necessary to accumulate all the available results in one paper with extensive analysis that will help the readers to get enough information all together. There are some review papers available about thermal conductivity [82,83] and viscosity [84] of nanofluid. As per our knowledge there is no review paper available about the specific heat of nanofluids. The objective of this paper is to provide details information about temperature, volume fraction, and particle diameter effect over the specific heat of nanofluids. Hopefully, this paper will satisfy the scientific community with enough information about specific heat capacity of nanofluid. In the subsequent sections preparation methods used by the researchers, experimental results concerning volume fraction and temperature effects on specific heat, theoretical models and correlations for volume concentrations, temperature, and particle diameter have been described, consecutively.

2. Research methods

2.1. Nanofluid preparation

Preparation of nanofluids is important for the measurement of specific heat of nanofluid. Since particle agglomeration depends on the preparation method of nanofluid. There are two techniques mainly used for synthesizing nanofluids: single step method and two step method. Most of the researches used two step dispersion method [64,84–86] and ultrasonic vibrations for proper mixtures of nanofluids.

Table 1
Literatures outline of nanofluids about specific heat for various parameters.

Year	Reference	Base fluid	Particle name (diameter nm)	Related to	
				V%	*T*
2012	Pandey and Nema [54]	W	Al_2O_3 (40–50)	√	√
2012	Choi and Zhang [55]	W	Al_2O_3 (50)	√	
2012	Chandrasekar et. al. [56]	W	Al_2O_3	√	
2012	Teng and Hung [57]	W	Al_2O_3 (20)	√	√
2008	Zhou and Ni [43]	W	Al_2O_3 (45)	√	√
1998	Pak and Cho [45]	W	Al_2O_3 (13); TiO_2 (27)	√	√
2012	Hanley et al. [58]	W	Al_2O_3 (50); SiO_2 (32); CuO (30)	√	√
2014	Elias et al. [49]	RC	Al_2O_3 (13)	√	√
2011	Murshed [59,60]	EG	Al_2O_3 (29); Al (80); TiO_2 (15 and 10×40)	√	
2012	Vajjha and Das [5]	(EG/W):(60/40)	Al_2O_3 (53); SiO_2 (30);CuO (29)	√	√
2009	Vajjha and Das [47]	(EG/W):(60/40)	Al_2O_3 (44);ZnO (77)	√	√
2008	Kulkarni et al. [61]	(EG/W):(50/50)	Al_2O_3(45)	√	√
2014	Nieh et al. [62]	(W/EG) (1:1) (v/v) with chitosan	Al_2O_3(10–20); TiO_2 (20–30)	√	√
2011	Sonawane et al. [63]	ATF	Al_2O_3(30 ± 10)	√	√
2011	Starace et al. [64]	PAO+S	Al_2O_3 needles	√	√
2007	Lee and Mudawar [65]	W, HFE 7100	Al_2O_3	√	
2014	Ho and Pan [66]	MHS	Al_2O_3 (<50 nm)	√	√
2014	Shin and Banerjee [67]	ACaSEu	Al_2O_3 (~10 nm)	√	√
2011	Shin and Banerjee [52]	ACSEu	SiO_2(20–30)	√	√
2010	Shin and Banerjee [68,69]	ACaSEu	SiO_2 (1–20)	√	√
2011	Starace et al. [64]	EG	SiO_2(50); OX50FS (40)	√	√
2009	Vajjha and Das [47]	DIW	SiO_2 (20)	√	√
2007	Namburu et al. [70]	(EG/W):(60/40)	SiO_2 (20)	√	√
2012	Ali Mohebbi [71]	Liquid Argon	Si_3N_4 (5)	√	√
2012	Saeedinia et al. [50,51]	PEO	CuO (50)	√	√
2010	Zhou et al. [72]	EG	CuO (25–50)	√	
2009	Pantzali et al. [73]	W	CuO (30)	√	√
2012	Robertis et al. [48]	EG	Cu (5–50)	√	√
2012	Pakdaman et al. [53]	HTO	MWCNT (5–50)	√	√
2013	Teng and Yu [74]	(W/EG) (1:1) (v/v) with chitosan	MWCNTs (20–30)	√	√
2012	Kumaresan et al. [75]	EG-DIW (30:70)	MWCNT (30–50)	√	√
2012	Castro et al. [76]	Ionic liquid [C4mim][PF_6]	MWCNT (13–16)	√	√
2014	Liu et al. [77]	Ionic liquid [HMIM]BF_4	Graphene (GE)	√	√
2013	Ghozatloo et al. [78]	W	Graphene	√	
2012	He et al. [79]	$BaCl_2$–W	TiO_2 (20)	√	√
2011	Starace et al. [64]	W/EG	OX50 FS (40)	√	√
2011	Starace et al. [64]	PAO+Chl	Fe@Fe_3O_4 (15–20)	√	√
2009	Nelson et al. [80]	PAO	Exfoliated Graphite (D 20 μ, 100 nm thickness)	√	√
2011	Starace et al. [64]	$Ca(NO_3)_2\cdot4H_2O$	Aerosil90 FS (20)	√	√
2011	Starace et al. [64]	MO	Bi (40); AlN (1 0 0); MCM; Fe@Fe_3O_4 (15–20); Al_2O_3 (1 0 0)	√	√
2011	Ghazvini et al.[81]	EO	Nanodiamond	√	√
2011	Starace et al. [64]	PAO	xGnP	√	√

Note: W, EG, DIW, RC, MWCNTs, ATF, MO, MHS, ACSEu, ACaSEu, PEO, EO, HTO, PAO, MCM, xGnP, and FS refer to water, ethylene glycol, distilled water, radiator coolant, multi-walled carbon nanotube, aviation turbine fuel, mineral oil, molten Hitec salt [mixture of sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3) and sodium nitrite ($NaNO_2$) in proportions of 7, 53, 40 mol%, respectively], salt, alkali chloride salt eutectics, alkali carbonate salt eutectics (Li_2CO_3–K_2CO_3), pure engine oil, engine oil, heat transfer oil, poly alpha olefin, mobile crystalline material, exfoliated graphite and fumed Silica, respectively. And *V%* and *T* means volume % or weight %, and temperature effect.

2.2. Specific heat measurement

Mainly, different types of differential scanning calorimeter (DSC) [64] is used to measure the specific heat of nanofluids [43,48,54,61,63]. Some authors prepared own setup for measuring specific heat of nanofluids. Some authors used simulation [55,71] for calculating specific heat and also have few literature where existing correlations [47] or Equation of Mixing theory [45] were used. Table 2 shows different theoretical and experimental methods used by the researchers to study the specific heat of nanofluids.

3. Theoretical studies

There are some correlations available about the specific heat of nanofluid. Even, some authors have investigated this property using these equations.

In 1998 Pak and Cho [45] first used the following equation for measuring specific heat of nanofluids.

$$C_{nf}=(1-\phi_v)C_w+\phi_v C_p \tag{4}$$

where, C is the specific heat of dispersed fluid, φ_v is volume fraction of nanoparticles, p is the particles, and w means water. Later some researchers modify and update this equation.

Then Xuan and Roetzel [46] in the year 2000 use the following Eq. (5). This equation is more fit than Eq. (4) for getting experimental data of nanofluid from latest literature reviews.

$$(\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_s \tag{5}$$

where,

$$\rho_{nf}=(1-\phi)\rho_f+\phi(\rho_p) \tag{6}$$

where, C_p is the specific heat of nanofluids, ρ is the density of nanofluid, and φ is volume fraction of nanoparticles. In addition, nf, f and s refer to nanofluid, fluid, and solid, respectively. Hanley et al. [58] did measurement and model validation of nanofluid specific heat capacity with DSC (TA Instruments Q2000). The specific heat capacities of water based SiO_2, Al_2O_3 and CO_2 nanofluids were measured with (0 to 0.3), (0 to 0.1) and (0 to 0.15) volume fractions, respectively. Test results were found to be in excellent agreement with Model II (Thermal equilibrium model, Eq. (5)), while the predictions of Model I (Mixing theory of ideal gas

Table 2
Different methods used in the literatures about specific heat.

Base fluid	Particle name	Particle size (nm)	Volume/weight (wt) fraction (%)	Measurement method	Ref.
W	Al_2O_3	40–50	2–4	Thermal conductivity instrument (TPS500 from Transient Plane Source Company)	[54]
W	Al_2O_3	50	0–10	Numerical simulation	[55]
W	Al_2O_3	45	0–21.7	PerkinElmer DSC 7	[43]
W	Al_2O_3	13	1.34–2.78	Equation of mixing theory	[45]
EG	Al_2O_3; Al; TiO_2	29; 80; 15 and 10×40	0–0.05	Double hot-wire experimental system with Wheatstone bridge circuit (self-developed)	[59]
RC	Al_2O_3	13	0.0–1.0	DSC 4000, PerkinElmer, USA and Xuan and Roetzel model	[49]
(EG/W):(60/40)	Al_2O_3	53	1–10	Reviewed by Eq. (4) [47]	[5]
(EG/W):(60/40)	Al_2O_3	44	2–10	Self-developed setup and correlation equation	[47]
(EG/W):(50/50)	Al_2O_3	45	2–6	Self-developed setup and correlation equation	[61]
ATF	Al_2O_3	30 ± 10	0.1–1	Self-developed calorimeter and mixing law	[63]
MO	Al_2O_3	100	0.001–0.005	DSC1 Stare, Mettler Toledo and compared with mixing law	[64]
MHS	Al_2O_3	(< 50 nm)	0.016–2 (wt)	PerkinElmer DSC 7	[66]
ACaSEu	Al_2O_3	($\sim$10 nm)	1 (wt)	DSC Model: Q20, TA Instruments, USA	[67]
ACSEu	SiO2	20–30	1	DSC Model: Q20, TA Instruments, Inc. and compared with mixing material equation	[52]
(EG/W):(60/40)	SiO_2	30	1–10	Reviewed by Eq. (4) [47]	[5]
EG	SiO_2	50	0.003–0.3	DSC1 Stare, Mettler Toledo and compared with mixing law equation	[64]
DIW	SiO_2	20	2–10	Self-developed setup and correlation equation	[47]
(EG/W):(60/40)	SiO_2	20	0–10	Self-developed setup and $Q = m(C_p)\Delta T$	[70]
Liquid Argon	Si_3N_4	5	4.15	Dynamics simulation	[71]
PEO	CuO	50	0.2–2	DSC F3 Maia, manufactured by NETZSCH-Germany	[50,51]
(EG/W):(60/40)	CuO	29	1–6	Reviewed by Eq. (4) [47]	[5]
EG	CuO	25–50	0.1–0.6	Analytically by quasisteady-state principle.	[72]
Water	CuO	30	2–8	DSC (Model: SETARAM C80D)	[73]
EG	Cu	5–50	0.5	DSC Q2000 TA Instruments	[48]
HTO	MWCNT	5–20	0.1–0.4	DSC F3 Maia, manufactured by NETZSCH-Germany	[53]
(EG/DIW) (30:70)	MWCNT	30–50	0.15–0.45	DSC(Model: TA instrument, Q200)	[75]
Ionic liquids [C4mim][PF6]	MWCNT	13–16	1–1.5	Experiment by DSC-111, Setaram, France	[76]
$BaCl_2$– W	TiO_2	20	0.167–1.130	DSC, made in German NETZSCH company, DSC-200 PC Phox	[79]
W	TiO_2	27	0.99–3.16	Equation of mixing theory	[45]
EG	OX50(fumed Silica)	40	0.005–0.05	DSC1 Stare, Mettler Toledo and compared with mixing law	[64]
EG/W	OX50(fumed Silica)	40	0.01	DSC1 Stare, Mettler Toledo and compared with mixing law	[64]
PAO+Chl	$Fe@Fe_3O_4$	15–20	0.001–0.024	DSC1 Stare, Mettler Toledo and compared with mixing law	[64]
MO	$Fe@Fe_3O_4$	15–20	0.001–0.024	DSC1 Stare, Mettler Toledo and compared with mixing law equation	[64]
(EG/W):(60/40)	ZnO	77	1–7	Self-developed setup and correlation equation	[47]
PAO	Exfoliated Graphite	20 μ, 100 nm (t)	0.3–0.6	DSC (Model: TA Instruments model Q100)	[80]
Ca(NO3) 2.4 W	Aerosil90(fumed Silica)	20	0.003	DSC1 Stare, Mettler Toledo and compared with mixing	[64]
MO	MCM		0.001–0.05	DSC1 Stare, Mettler Toledo and compared with mixing	[64]
MO	Bi	40	0.001	DSC1 Stare, Mettler Toledo and compared with mixing	[64]
MO	AlN	100	0.001–.05	DSC1 Stare, Mettler Toledo and compared with mixing	[64]
EO	Nanodiamond		0.2–2	DSC 200 F3, Netzsch, Germany	[81]
PAO	xGnP		0.01	DSC1 Stare, Mettler Toledo and compared with mixing	[64]

Note: W, EG, DIW, RC, MWCNTs, ATF, MO, MHS, ACSEu, ACaSEu, PEO, HTO, PAO, MCM, AlN, xGnP and FS refer to water, ethylene glycol, distilled water, radiator coolant, multi-walled carbon nanotube, aviation turbine fuel, mineral oil, molten Hitec salt, alkali chloride salt eutectics, alkali carbonate salt eutectics (Li_2CO_3–K_2CO_3), pure engine oil, heat transfer oil, poly alpha olefin, mobile crystalline material, aluminum nitride, exfoliated graphite, and fumed silica, respectively. "(wt)" means weight % considered and nothing means volume % considered.

mixture, Eq. (4)) deviated very significantly from the data. Therefore, Eq. (5) is recommended for nanofluids. Murshed [59,60] also checked that Eq. (5) is in reasonably good agreement with experimental results, as the maximum deviations between the calculated data and the measured values are found to be 0.8%, 5.5%, and 7% for Al–EG, TiO_2–EG, and Al–EO nanofluids, respectively.

Kulkarni et al. [61] derived Eq. (7) that is related with specific heat. They used this equation to verify the accuracy of the specific heat measurement apparatus and the experimental procedure.

$$C_{pnf} = Q/m(\Delta t/\Delta T) \tag{7}$$

In this equation, Q refers to the rate of heat supplied to fluid, m is the mass of fluid, Δ is the difference, t is the time, and T is the temperature.

Vajjha and Das [47] showed that the measured values of specific heat have not good agreement with the existing equations for the specific heat of nanofluids. Therefore, a new general correlation (8) was developed for the specific heat as a function of particle volumetric concentration, temperature, and the specific heat of both particles and base fluids for the nanofluids mentioned in Table 3. The correlation predicts the specific heat values of each nanofluid within an average error of about 2.7% [47].

$$(C_{pnf}/C_{pbf}) = [(A \times T) + B \times (C_{pbf})]/(C + \phi) \tag{8}$$

where C_p is specific heat, T means temperature, s is solid particle, φ is volumetric concentration, nf refers to nanofluid, bf is base fluid, and A, B, C are curve fit coefficients of different nanofluids shown in Table 3. This new correlation is applicable for concentrations up to 10% for Al_2O_3 and SiO_2 nanofluids, and up to 7% for

Table 3
Curve-fit coefficients for different nanofluids [5,47].

Nanofluid	A (in 2009)	A (in 2012)	B	C	Max. error (%)	Avg. absolute error (%)
Al_2O_3	0.000891	0.24327	0.5179	0.4250	5	2.23
SiO_2	0.001769	0.48294	1.1937	0.8021	3.1	1.5
ZnO	0.0004604	0.12569	0.9855	0.299	4.4	2.7

ZnO nanofluids of (EG–W: 60/40) and water, within the temperature range of 315–363 K. Vajjha and Das [5] again reviewed and updated their correlation with curve-fit coefficients which are shown in Eq. (9) and Table 3. They also checked for nanofluid with CuO nanoparticle.

$$\frac{C_{pnf}}{C_{pbf}} = \frac{[(A(T/T_o)) + B(C_{pp}/C_{pbf})]}{(C+\phi)} \tag{9}$$

Zhou et al. [72] derived Eq. (10) from Eq. (4) and used for (CuO–EG) nanofluid.

$$C_{pnf} = [(1-\phi)\rho_f C_{pf} + \phi\rho_{np} C_{pnp}]/[\phi_f \rho_f + (1-\phi)\rho_{np}] \tag{10}$$

where the authors considered volume fraction and density of base fluid and nanoparticles separately.

Shin and Banerjee [52] proposed Eq. (11) to compare the theoretical predictions of specific heat from the thermal equilibrium model of mixture.

$$C_{p,t} = (\phi\phi_p C_{p,p} + \phi_f \rho_f C_{p,f})/(\phi_p \rho_p + \phi_f \rho_f) \tag{11}$$

where, $C_{p,t}$ is effective specific heat capacity of mixture, f, p, φ, ρ refers to fluid, particle, volume fraction, and density correspondingly. After small modifying, Shin and Banerjee [67] proposed a new correlation (12) for non-aqueous alkali salt base nanofluids.

$$C_{p,t} = \frac{\rho_{np}\phi_{np}C_{p,np} + \rho_s\phi_s C_{p,s} + \rho_{ns}\phi_{ns}C_{p,ns}}{\rho_{np}\phi_{np} + \rho_s\phi_s + \rho_{ns}\phi_{ns}} \tag{12}$$

where, np, ns and s means nanoparticle, nanostructure and pure salt. They mentioned that, further investigation and new instruments will be needed to measure the properties of nanostructures as it is very difficult to measure these by current technology.

Pakdaman et al. [53] developed correlation (13) based on the least square method, which can satisfactorily predict the specific heat capacity of MWCNT- heat transfer oil.

$$(C_{pbf} - C_{pnf})/C_{pbf} = (0.0128 \times T + 1.8382) \times \phi^{0.4779} \tag{13}$$

where φ is weight concentration (0, 0.001, 0.002 or 0.004) and T is the temperature ranging from 313 to 343 K.

Kumaresan and Velraj [75] used Eq. (14) to check the accuracy of DSC to determine the specific heat of nanofluids.

$$(C_p)_{nf} = \Delta Q_{nf}/(m_{nf} \times \Delta T_{nf}) \tag{14}$$

where ΔQ_{nf} is effective heat flow, m_{nf} is mass flow rate of the nanofluid, and ΔT_{nf} is temperature range. Also the authors [75] described another Eq. (15), which was used to investigate the agreement of experimental data with numerical data.

$$(C_p)_{nf} = [(1-\phi)(\rho C_p)_f + \phi(\rho C_p)_n]/[\phi\rho_n + (1-\phi)\rho_f] \tag{15}$$

where φ is volume fraction of nanofluids, ρ is density, nf refers to nanofluid, f is fluid, n is nanoparticle. This equation is more acceptable by some other researchers and used to find out the specific heat of nanofluids analytically [87,88].

Sekhar and Sharma [44] developed a correlation of regression after reviewing 81 experimental data points of water-based Al_2O_3, CuO, SiO_2 and TiO_2 nanofluids from the literature which is valid for

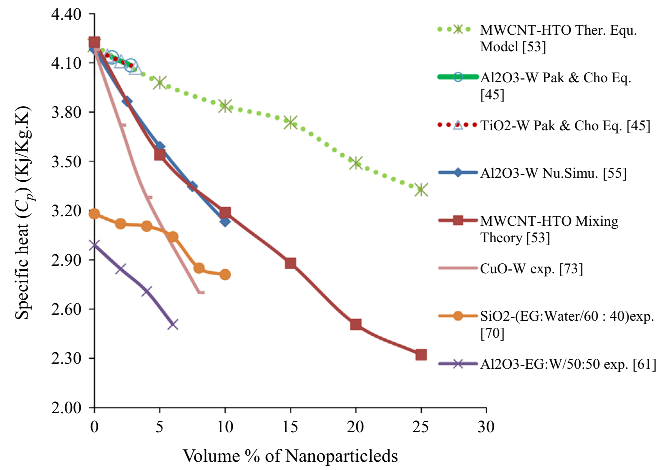

Fig. 1. Specific heat of nanofluids decreasing with the increase of volume (%) of nanoparticles.

$20 < T_{nf} < 50$ °C, $15 < d_p < 50$ nm and $0.01\% < \varphi < 4.00\%$.

$$C_{pr} = 0.8429\left(1+\frac{T_{nf}}{50}\right)^{-0.3037}\left(1+\frac{d_p}{50}\right)^{0.4167}\left(1+\frac{\phi}{100}\right)^{2.272} \tag{16}$$

They observed that calculated values were in good agreement with the experimental data of different authors with a deviation of +10% and −8%, thus confirming the validity of the expression. Ghazvini et al. [81] made a correlation (17) of specific heat of nanofluids with 1% weight fraction of Nanodiamond in Engine oil as a function of temperature (T in K, C_p in J/kg-K, and $278\,K \le T \le 373\,K$) and polynomial goodness of fit R^2=0.994 (residual degrees of freedom adjusted).

$$C_p = 2.62 - 6 \times 10^{-3}T + 2 \times 10^{-5}T^2 \tag{17}$$

4. Experimental and theoretical results

4.1. Effect of volume concentration on specific heat

Some literature are available about the effect of volume concentration on the specific heat of nanofluids [61]. Some researchers [45,53,89] showed specific heat of nanofluid is decreased with the increase of volume fraction. Fig. 1 indicates that specific heat of nanofluid decreases with the enhancement of volume fraction. Choi and Zhang [55] showed that for 1 to 10 vol% of Al_2O_3–W nanofluids specific heat decreased from 7.57 to 25%. Kulkarni et al. [61] observed that specific heat decreased from 4.84 to 16.14% for 2 to 6 vol% of nanoparticles concentration. Zhou and Ni [43] showed that, for the increasing of nanoparticle vol% from 0 to 25% specific heat of Al_2O_3–W nanofluid decreased up to 21% based on Mixing Theory and 45% based on Thermal Equilibrium Model. Namburu et al. [70] experimentally investigated the specific heat of 0 to 10 vol% SiO_2 nanoparticles with (EG/W):(60/40) mixture and found that specific heat falls up to 12% with the increase of volume concentration. Murshed [59,60] have made simultaneous investigation of specific heat of TiO_2–EG, Al_2O_3–EG, Al–EG and Al–EO nanofluids with different volume fraction (0 to 0.05) and shape of nanoparticles by using double hot-wire experimental system with Wheatstone bridge circuit. They also found that, specific heat of nanofluids decreasing with the increase of the volume fraction of nanoparticles. Bergman [90] and Lee and Mudawar [65] showed that, specific heat of Al_2O_3–water nanofluid and Al_2O_3- HFE 7100 nanofluid decreasing with the increase of volume % of nanoparticles. Similarly, Pantzali et al. [73]

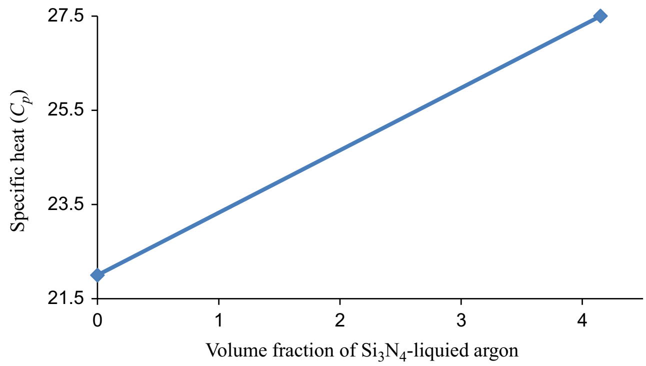

Fig. 2. Specific heat of nanofluids increasing with the increase of volume (%) of nanoparticles [71].

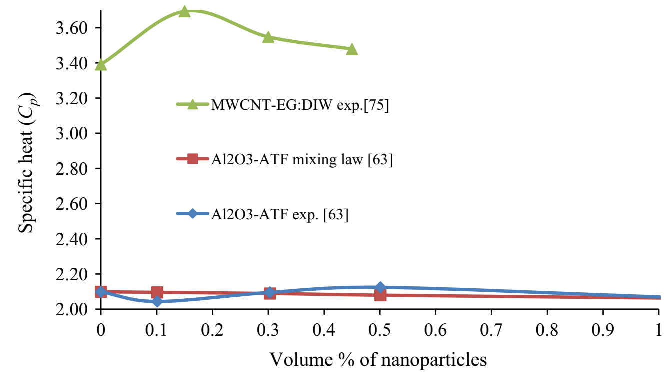

Fig. 3. Uneven effects of volume fraction on the Specific heat of nanofluids.

experimentally found (by DSC) that for the rise of 2 to 8 vol% of CuO–water nanofluid, specific heat decreased on an average 20%. Vanapalli and Brake [91] made assessment of thermal conductivity, viscosity and specific heat of nanofluids with TiO_2 in single phase laminar internal forced convection. They have considered specific heat ratios of nanofluids and base fluids are 1 and below 1 i.e. 0.9, 0.8, 0.7 and 0.6. Therefore, they assessed specific heat of nanofluids with considering the specific heat of nanofluids lower than base fluid. Ghozatloo et al. [78] also showed the decrement of specific heat of Graphene–water nanofluid and this decrement was increasing with the increase of weight fraction of Graphene nanoparticles. The highest decrement was 8.11% after adding 0.1 wt% of graphene. Liu et al. [77] investigated the specific heat of ionic liquid [1-hexyl-3-methylimidazolium tetrafluoroborate ([HMIM]BF4)] based nanofluids containing graphene nanoparticles (by DSC, Q20, TA Instruments, USA) with sapphire method. They also found that the specific heat of the Ionanofluid containing 0.03 wt% graphene decreases by approximately 1.5% at each tested temperature and accordingly decreases by 3% when the graphene loading is 0.06 wt%, as compared with that of the base fluid.

On the other hand, Mohebbi [71] got totally opposite result as specific heat of nanofluid increased with the increase of volume fractions of Si_3N_4 nanoparticle in Liquid Argon and 18.6 to 27% increased specific heat found for 4.15 vol% of nanoparticles as shown in Fig. 2. However, some investigation found that specific heat increases accordingly with the increase of volume fraction up to some level. Sonawane et al. [63] got very exciting results for Al_2O_3–ATF (aviation turbine fuel) nanofluid. For 0.1 vol% of Al_2O_3, specific heat of the nanofluid found lower than the base fluid but for 0.3 and 0.5 vol% of Al_2O_3, the specific heat of the nanofluid found higher than that of base fluid. For 1 vol% of nanoparticle, it is again less than the base fluid, which has shown in Fig. 3. It is quite interesting that the heat capacity or specific heat of 0.15 vol% of MWCNT- (EG: DIW/30:70) nanofluid is greater than the base fluid but it is decreasing with the increase of volume (%) of MWCNT though it is also higher than that of base fluid [75]. The reason behind these phenomena has been analyzed in discussion section. Shin and Banerjee [67] also experimentally measured the specific heat capacity of pure salt eutectic (Li_2CO_3–K_2CO_3) and nanofluids of 1% mass concentration of Al_2O_3 nanoparticles (with nominal diameter of ~10 nm) in the salt eutectic by DSC instrument (Model: Q20, TA Instruments). Authors' prepared 2 samples of nanofluid and have run the experiment 4 times for each sample and found averagely 33% and 31% enhancement in specific heat capacity for nanofluid 1 and nanofluid 2, respectively. On an average 32% enhancement has found for the salt base nanofluid compared to the base fluid. Ho and Pan [66] discovered the optimal concentration of Al_2O_3 nanoparticles in Molten Hitec Salt (MHS) (mixture of sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3) and sodium nitrite ($NaNO_2$) in proportions of 7, 53, 40 mol%, respectively) with 20 wt% of Al_2O_3–water nanofluid to maximize its specific heat capacity. They got the best enhancement on specific heat of the MHS nanofluid with 0.063 wt% of Al_2O_3 nanoparticles which is 19.9% compared to base fluid. After that, the enhancement% of specific heat of the nanofluids decreased with the increase of wt% of the Al_2O_3 nanoparticles and negative enhancements have found with 2 wt% of Al_2O_3 nanoparticles at all temperatures.

In addition, some researchers add dispersant to make more stable nanofluids and to increase the specific heat of the fluids. As Chitosan (Ch) is non-toxic and biodegradable, and is widely used in medicine, agriculture, chemical and food processing areas without causing environmental pollution. Therefore, in the literature generally they add Ch in the base fluid to increase the stability and specific heat. Nieh et al. [62] prepared Al_2O_3 and TiO_2 nanocoolant (NC) with 0.5, 1.0 and 2.0 wt% of nanoparticles in water with dispersant (Chitosan) and then mixed with EG at a 1:1 (v/v) ratio to form the NC_1–NC_3 for Al_2O_3 and NC_4–NC_6 for TiO_2. For adding the dispersant (Chitosan) to EG/W, the specific heat of the NCs increased but, it was gradually decreased with the increase of wt% of Al_2O_3 and TiO_2. They measured the specific heat of the NCs for temperatures range from 80 to 95 °C by the DSC (Q20, TA, USA) and a vapour compression refrigeration system (RCS40, TA, USA) in a high-purity nitrogen (5 N) atmosphere. They found the specific heat of the Al_2O_3 NC is higher than that of the TiO_2 NC, and the specific heat of the samples increased with the temperature. The highest specific heat ratios of NC1, NC2, NC3, NC4, NC5, and NC6 [where, NC1 (EG/0.5 wt% Al_2O_3/W nanofluid), NC2 (EG/1.0 wt% Al_2O_3/W NF), NC3 (EG/2.0 wt% Al_2O_3/W NF), NC4 (EG/0.5 wt% TiO_2/W NF), NC5 (EG/1.0 wt% TiO_2/W NF) and NC6 (EG/2.0 wt% TiO_2/W NF)] increased by 2.1%, 1.9%, 0.1%, 0.7%, 0.8%, and −3.2%, respectively, compared with the EG/W (with Ch) for all experimental parameters. Teng and Hung [57] investigated the deviation between the calculated (with Eqs. (3) and (4)) and experimental results of the specific heat and density of Al_2O_3–water nanofluids with 0.5, 1.0 and 1.5 wt% of the nanoparticles and added 0.2 wt% of dispersant (Chitosan) in all mixtures. They found good agreement with calculated and experimental value for 0.5 wt% of Al_2O_3 nanoparticles in water. The deviation of specific heat is in the range of −0.07% to 5.88% and −0.35% to 4.94%, respectively. The calculated results of density and specific heat show a trend of greater deviation as the concentration of nanofluid increases. This may be due to specific surface area, interface layer, grain size, porosity and adsorption. Similarly, Teng and Yu [74] also used chitosan as a dispersant in the MWCNTs/W nanofluids and they got highest Zeta potential with 0.4 wt% of Ch in the nanofluid. Then they add with EG at a 1:1 (v/v) ratio to form the nano coolant, NC1 (EG/0.1 wt% MWCNTs/W), NC2 (EG/0.2 wt% MW CNTs/W) and NC3 (EG/0.4 wt% MWCNTs/W nanofluid). The

Table 4
Specific heat increases or decreases as per volume concentration of nanoparticles.

Researchers	Base fluid	Particle name (nm)	Volume/weight (wt) fraction (%)	Specific heat decrement (−) or increment (+) (%)
Pandey and Nema [54]	Water	Al_2O_3 (40–50)	2–4	(−) 4–20
Choi and Zhang [55]	Water	Al_2O_3 (50)	2.5–10	(−) 7.57–25
Chandrasekar et al. [56]	Water	Al_2O_3	0–25	(−) 0–21(−) 0–45
Zhou and Ni [43]	Water	Al_2O_3 (45)	0–21.7	(−) 0–45.72
Pak and Cho [45]	Water	γAl_2O_3 (13)	1.34–2.78	(−) 1.10–2.27
Elias et al. [49]	RC	Al_2O_3 (13)	0.0–1.0	(−) 0–14
Vajjha and Das [5]	(EG/W):(60/40)	Al_2O_3 (53)	1–10	(−)13.2 (Approx.)
Vajjha and Das [47]	(EG/W):(60/40)	Al_2O_3 (44)	2–10	(−) 1.3–23.11
Kulkarni et al. [61]	(EG/W):(50/50)	Al_2O_3 (45)	2–6	(−) 4.84–16.14
Nieh et al. [62]	(W/EG) (1:1) (v/v) with chitosan	Al_2O_3 (10–20)	0.5, 1.0, 2.0 (wt)	(+) 2.1, 1.9, 0.1
Sonawane et al. [63]	Aviation turbine fuel	Al_2O_3 (30 ± 10)	0.1, 0.3, 0.5, 1	(−)2.6, (−) 0.15, (+)1.22, (−)1.38
Starace et al. [64]	mineral oil,	Al $_2O_3$ (1 0 0)	0.001–0.005	(+) 2–3
Starace et al. [64]	PAO+ surfactants	Al_2O_3 needles	0.004–0.0075	(−) 1–2
Lee and Mudawar [65]	W; HFE 7100	Al_2O_3	0–5	(−)(0–4); (−)(0–2)
Ho and Pan [66]	MHS (Molten Hitec Salt) (at 200 °C)	Al_2O_3 (< 50 nm)	0.016, 0.063, 0.125, 0.25, 0.5, 1, 2 (wt)	(+) 9.5, 19.9, 14.7, 9.8, 7.8, 6.1, (−) 4.1
Shin and Banerjee [67]	ACaSEu	Al_2O_3 (~10 nm)	1 (wt)	(+) 32
Shin and Banerjee [68,69]	ACaSEu	SiO_2 (1–20)	1, 1.5 (wt)	(+) (19–24), (+) (74–101)
Shin and Banerjee [52]	ACSEu	SiO_2 (20–30)	1	(+) 14.5 (Avg.)
Starace et al. [64]	Ethylene glycol	SiO_2 (50)	0.003–0.3	(−)15–(+) 2
Vajjha and Das [47]	DIW	SiO_2 (20)	2–10	(−) 3.98–14.66
Vajjha and Das [5]	(EG/W):(60/40)	SiO_2 (30)	1–10	(−) 10 (Approx.)
Namburu et al. [70]	(EG/W):(60/40)	SiO_2 (20)	0–10	(−) 0–12
Ali Mohebbi [71]	Liquid argon	Si_3N_4 (5)	4.15	(+) 18.6–27
Saeedinia et al. [50,51]	Pure engine oil	CuO (50)	0.2–2	(−) 16–28
Vajjha and Das [5]	(EG/W):(60/40)	CuO (29)	1–6	(−) 24 (Approx.)
Zhou et al. [72]	EG	CuO (25–50)	0.1–0.6	(−) 1.16–5.04
Pantzali et al. [73]	Water	CuO (30)	2–8	(−) 20 (Avg.)
Robertis et al. [48]	EG	Cu (5–50)	0.5	(−) 1.94–12
Pakdaman et al. [53]	Heat transfer oil	MWCNT (5–20)	0.1–0.4	(−) 21.2–42
Teng and Yu [74]	(W/EG) (1:1) (v/v) with chitosan	MWCNTs (20–30)	0.1, 0.2, 0.4	(+)(3.2–3.5), (+)(0.5–0.8),(−)(2.7–3.9)
Kumaresan and Velraj [75]	EG-DIW (30:70)	MWCNT (30–50)	0.15–0.45	(+) 2.31–9.35
Castro et al. [76]	Ionic liquids [C4mim][PF6]	MWCNT (13–16)	1, 1.5	(+) 8 (highest)
Liu et al. [77]	Ionic liquid [HMIM]BF_4	Graphene (GE)	0.03, 0.06 (wt)	(−) 1.5, (−) 3
He et al. [79]	$BaCl_2$– H_2O	TiO_2 (20)	0.167–1.130	(−) 2.3–12.4
Pak and Cho [45]	Water	TiO_2 (27)	0.99–3.16	(−) 0.81–2.61
Nieh et al. [62]	(W/EG) (1:1)(v/v) with chitosan	TiO_2 (20–30)	0.5, 1.0, 2.0 (wt)	(+) 0.7, 0.8, (−) 3.2
Starace et al. [64]	Ethylene glycol	OX50(fumed silica) (40)	0.005–0.05	2. (−)1–(+) 3
Starace et al. [64]	Water/ethylene glycol	OX50(fumed silica) (40)	0.01	(+) 1
Starace et al. [64]	PAO+Chl	Fe@Fe_3O_4 (15–20)	0.001–0.024	(−) 10–(+) 6
Starace et al. [64]	Mineral oil	Fe@Fe_3O_4 (15–20)	0.001–0.024	(−) 10–(+) 6
Vajjha and Das [47]	(EG/W):(60/40)	ZnO (77)	1–7	(−) 4.23–18.08
Nelson et al. [80]	PAO (polyalphaolefin)	Exfoliated Graphite (dia 20 μ, 100 nm thickness)	0.3, 0.6	(+) ~50
Starace et al. [64]	$Ca(NO_3)_2 \cdot 4H_2O$	Aerosil90 (fumed silica) (20)	0.003	(+) 5
Starace et al. [64]	Mineral oil	Mobile crystalline material	0.001–0.005	(+) 2–3
Starace et al. [64]	Mineral oil	Bi (40)	0.001	(−) 2
Starace et al. [64]	Mineral oil	AlN (aluminum nitride) (1 0 0)	0.001–.05	(+) 2–3
Ghazvini et al. [81]	EO	Nanodiamond	0.2–2	(+) 7–30
Starace et al. [64]	PAO	xGnP (exfoliated graphite)	0.01	(+) 1

specific heat ratios increased by 3.2–3.5% for NC1, 0.5–0.8% for NC2 and decreased by 2.7–3.9% for NC3 compared to EG/W (using Ch) with temperature changes from 80 to 95 °C. Therefore, specific heat of the NCs increased with the increase of temperature and gradually decreased with the increase of volume concentration of MWCNTs though, after adding dispersant (Ch) specific heat of the mixture was higher compared to pure EG/W. Therefore, It is hard to summaries the above discussion about the effect of volume fraction of nanoparticles on specific heat of nanofluid. The summery of specific heat increment and decrement based on volume concentration of nanoparticles are shown in Table 4. The arrangement of the table has been done based on the types of nanoparticle and then the base fluid.

From Table 4, it has been seen that, generally the specific heat of the nanofluid increasing with the increase of particle diameter for the same nanofluids. Wang et al. [92] also investigated the

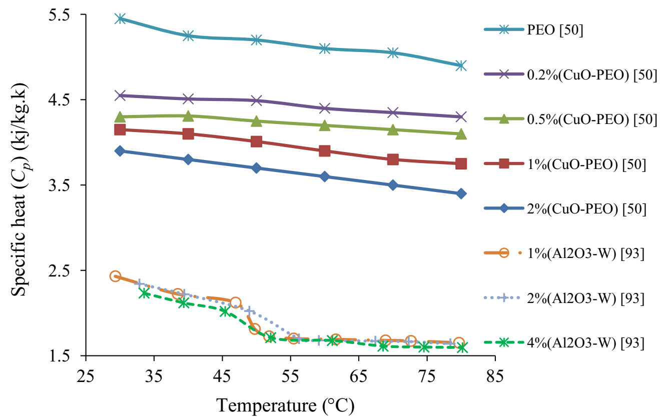

Fig. 4. Specific heat decreases with the increase of temperature.

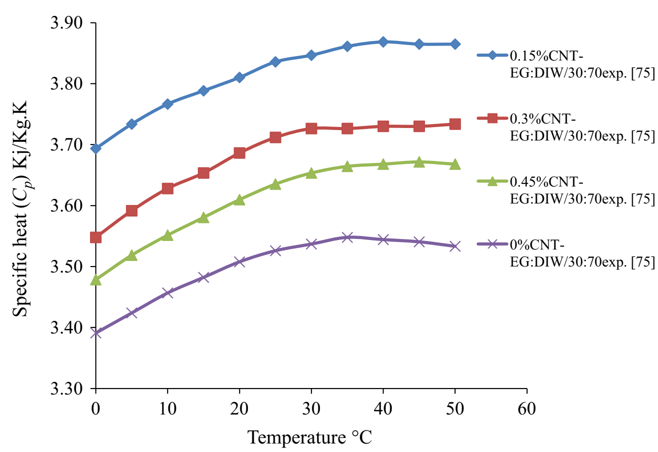

Fig. 5. Effect of temperature on specific heat of nanofluids.

surface and size effects on the specific heat capacity of CuO nanoparticles. They showed that, specific heat capacity of CuO nanoparticles are increasing with the increase of diameter of the nanoparticles with temperature range up to 325 K.

4.2. Effect of temperature on specific heat

Most of the literatures showed that temperature has significant effect over specific heat of nanofluids. Robertis et al. [48] made experiments with Cu–EG nanofluid and found that the specific heat of that nanofluid decreased for nanoparticles suspension in base fluid and it increasing with the increase of temperature. But interesting is that when Saeedinia et al. [50] suspended CuO nanoparticles in Pure Engine Oil (PEO) then the specific heat of that nanofluid decreasing with the increase of volume concentrations of CuO nanoparticles and the values of specific heat also decreasing with the increase of temperatures. Due to base fluid PEO, when temperature is increasing then the specific heat) is decreasing 16 to 28%. Gangacharyulu [93] also showed that the specific heat of Al_2O_3–water nanofluids decreased with the increase of temperature however, above 50 °C specific heat decrement was found to be very lower. Ho and Pan [66] also showed that, enhancement % of the specific heat of the MHS based Al_2O_3 nanofluids with almost all concentration also decreasing with the increase of temperature from 200 to 350 °C. The effect of concentration is much weaker at 350 °C compared to lower temperatures. The peak enhancement at concentrations of 0.063 wt% and 0.125 wt% was only 6.1% at 350 °C and increasing the concentration above 0.5 wt% has a negative effect on specific heat capacity. Fig. 4 shows the decreasing trend of specific heat with the rise of temperatures.

Similarly, Shin and Banerjee [52] reported that the specific heat capacity of alkali metal chloride salt eutectics doped with SiO_2 nanoparticles enhanced about 14.5% for 1% mass concentration of SiO_2 and it is decreasing with the increase of temperature. Ali Mohebbi [71] also have done dynamic simulation for 4.15% of Si_3N_4-Liquid Argon nanofluid and got the same result as specific heat falls with the rise of temperature and increased with the rise of volume fractions of nanoparticles.

However, quite interesting is that, Kumaresan and Velraj [75] investigated the heat capacity or specific heat of MWCNT- (EG: DIW/30:70) nanofluid was continuously increasing with the increase of temperature up to 30 °C but it is decreasing with the increase of volume (%) of MWCNT though it is also higher than that of base fluid. It also has been seen in Fig. 5 that, for above nanofluid with 0.3% CNT, specific heat was not increasing with the increase of temperature above 30 °C, even it was slightly decreasing with the increase of temperature. Similarly, at 35 °C specific heat of the nanofluids with 0.15% and 0.45% CNT were not increase with the increase of temperature and even at 45 and 50 °C the specific heat of those nanofluids slightly decreased. In the same way, the specific heat of the base fluid (EG:DIW/30:70) increasing with the increase of temperature up to 35 °C but after that, it was decreasing with the increase of temperature. Liu et al. [77] also got interesting results for the specific heat of ionic liquid [HMIM]BF4 based nanofluids with graphene as advanced heat transfer fluids for medium-to-high-temperature applications by differential scanning calorimeter (DSC, Q20, TA Instruments, USA) with sapphire method. They showed that, the specific heat of the Ionanofluid containing 0.03 wt% graphene varies from 2.258 to 2.363 J/g °C with the temperature ranges from 25 to 215 °C, and accordingly varies from 2.236 to 2.260 J/g °C when graphene was 0.06 wt%. It has been seen that, the specific heat of the Ionic Liquid (IL) and the Ionanofluids increases with the increase of temperature. However, there was an unexpected jump of specific heat at the temperature range from 60 to 150 °C for all the samples and the author mentioned that, the reason still remains unclear to them. Ghazvini et al. [81] measured the specific heat of Nanodiamond- Engine oil nanofluid with 0.002, 0.01 and 0.02 weight fraction (by DSC 200 F3, Netzsch, Germany). They found that, specific heat of all fluids increases with the increase of temperature, and weight fractions. Nieh et al. [62] and Teng and Yu [74] also showed that, the specific heat of the (nanocoolants) NCs increased with the increase of temperature range from 80 to 95 °C.

Vajjha and Das [5] shown that the specific heat of EG/W mixture of 60:40 with SiO_2, CuO, Al_2O_3 nanoparticles were increased with the increase of temperature but specific heat decreased with the increase of volume fractions which is shown in Fig. 6. Nanofluids with MWCNT have different results for different base fluids. Pakdaman et al. [53] compare the experimental data of Pak and Cho [45] and Xuan and Roetzel [46] with doped MWCNT (dia 5–20 nm) in pure Heat Transfer Oil (HTO) and observed that dispersing nanoparticles in the base fluid results in a decrease in the specific heat capacity of the fluid and it is increasing with the increase of temperature. For example the specific heat capacity of 0.4 wt% nanofluid is almost 42% less than that of the base fluid at 40 °C. Robertis et al. [48] experimentally found that specific heat of EG and Cu nanoparticle at different volume fraction of nanofluid increased with the increase of temperature as shown in Fig. 6.

On the other hand, He et al. [79] investigated on TiO_2—Phase Change Material ($BaCl_2$/W) nanofluid and reported that the specific heat is reduced for the addition of nanoparticles and the temperature has very less effects on the specific heat of the above nanofluid. Along with the increase of volume concentration of TiO_2

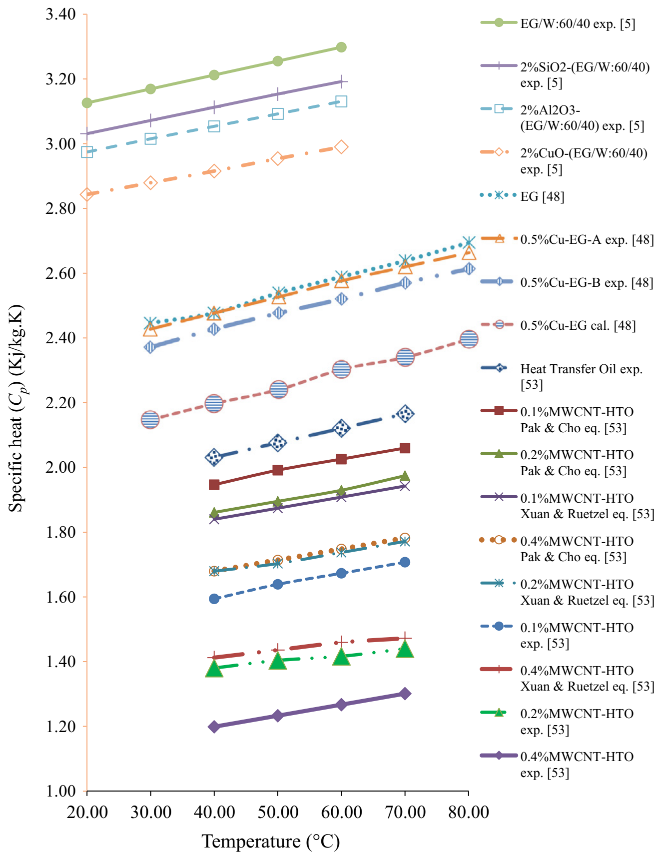

Fig. 6. Specific heat of nanofluids increases accordingly with temperature.

nanoparticles in Phase Change Material ($BaCl_2$/W), the specific heat decreases even at different temperatures which are shown in Fig. 7. It has been seen that the maximum change is 3.1% for 1.13 vol% nanofluids from 10 to 80 °C, which could be negligible in small temperature range.

Therefore, it is very difficult to conclude the above discussion in a single sentence about volume concentration and temperature effect on specific heat of nanofluids. However, generally, if the specific heat of nanoparticles is less than the base fluid then the specific heat of suspension will lessen otherwise it will rise.

5. Discussion

The specific heat (C_p) of nanofluids can be increased or decreased with respect to base fluids. It depends on the types and volume concentration of nanoparticles, temperatures and types of base fluids. In which places temperature changes required very quickly in that place it will be very beneficial if low specific heat capacitive fluid can be used. Based on this, nanofluids are potential fluids to use the above mentioned places as specific heat of the most common nanofluids decrease with the rise of volume fraction and temperature [45,50,52,73]. Though some conflict results is proportional among the specific heat, volume fraction and temperature [5,53,71]. Therefore, where high temperature range required in that places the high heat capacitive nanofluids can be used. He et al. [79] described two reasons which effect the specific heat of nanofluids. First, the specific heat of both nanoparticles and base fluid effect the dispersion. If the nanoparticles' specific heat is less than the basic liquid, the specific heat of suspension will be decreased. Otherwise it will increase, for instance, the specific heat of carbon

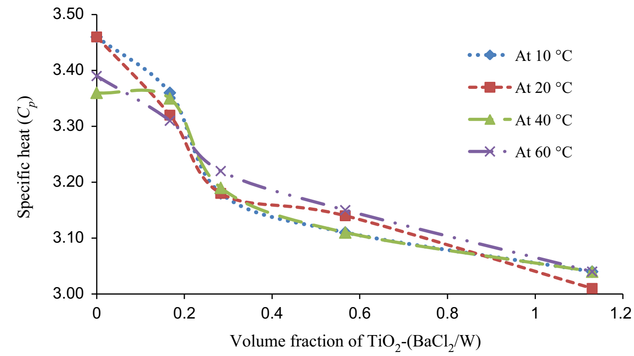

Fig. 7. Insignificant effects of temperature on the Specific heat of nanofluids[79].

nano-tube (CNT) is higher than that of ethylene glycol, the specific heat of CNT–glycol nanofluid is enhanced and again as the specific heat of Al_2O_3 nanoparticle less than water and EG therefore, Al_2O_3–water and Al_2O_3–EG nanofluids have lower specific heat capacity than the base fluids [5,55]. On the other hand, the interfacial free energy of solid–liquid is changed with suspended nanoparticles. Because of the bigger specific surface area of nanoparticles, its surface free energy has a greater proportion in the system capacity, which affects the specific heat of composite materials. Therefore, to get the required specific heat from nanofluid we need to mix the proper nanoparticles in the proper base fluid with proper volume concentration and also need to take care about the temperature.

6. Conclusion

From the previous literature it is clear that, nanofluids are potential to increase the heat transfer performance of the heat recovery systems. The performance parameters like: energy and exergy effectiveness is related to the specific heat of the nanofluids. Therefore, in this paper the relationships among the volume concentrations and temperatures with specific heat capacity of different nanofluids using different types and sizes of nanoparticles and base fluids have been reviewed. Most of all correlations available in the literature to measure the specific heat of the nanofluids have been discussed and analyzed. Measurement methods and instruments used to measure the specific heat of the nanofluids also mentioned in the table. All the results and findings available in the literature are critically accumulated and presented in different graphs, tables and in the text. Through this study it is found that volume fractions, temperature and different types and sizes of nanoparticles and base fluids have significant effects on specific heat of nanofluids. From all the above results and discussions it has been concluded that, specific heat of the most of the common nanofluids decreases with the increase of volume fractions though, there are some inconsistent results about the effect of specific heat of nanofluids with volume concentrations. It has been seen that, for the same nanofluids, the specific heat is higher for the nanofluids with high diameter of the nanoparticles. The dispersant also have significant effects on the specific heat of the nanofluids. Usually, the specific heat of the nanofluids increased compared to base fluids after adding dispersant in the mixtures. There are contradictory results among the effects of temperatures on specific heat of the nanofluids. But generally, if low specific heat capacitive nanofluid needed then nanoparticles with low specific heat capacity should be suspended in the base fluid and vice versa. Therefore, to get the required specific heat capacitive nanofluids, it is recommended to know the specific heat of the base fluids and nanoparticles. From the above reviews, researchers and related peoples will get required information to make decision about the specific heat of nanofluids.

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References

[1] Saidur R, Ahamed JU, Masjuki HH. Energy, exergy and economic analysis of industrial boilers. Energy Policy 2010;38(5):2188–97.
[2] Leong KY, Saidur R, Mahlia TMI, Yau YH. Modeling of shell and tube heat recovery exchanger operated with nanofluid based coolants. Int J Heat Mass Transfer 2012;55(4):808–16.
[3] Syam Sundar L, Singh MK. Convective heat transfer and friction factor correlations of nanofluid in a tube and with inserts: a review. Renewable Sustainable Energy Rev 2013;20(0):23–35.
[4] Choi SUS. Developments and applications of non-newtonian flows. ASME FED 1995;231(66):99–103.
[5] Vajjha RS, Das. DK. A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power. Int J Heat Mass Transfer 2012;55(15–16):4063–78.
[6] Shahrul IM, Mahbubul IM, Saidur R, Sabri MFM, Amalina MA, Khaleduzzaman SS. Global effects of MWCNT-W nanofluid in a shell & tube heat exchanger. Adv Mater Res 2014;832:154–9.
[7] Xuan Y, Li Q. Investigation on convective heat transfer and flow features of nanofluids. J Heat Transfer 2003;125(1):151–5.
[8] Kakaç S, Pramuanjaroenkij A. Review of convective heat transfer enhancement with nanofluids. Int J Heat Mass Transfer 2009;52(13–14):3187–96.
[9] Wen D, Ding Y. Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. Int J Heat Mass Transfer 2004;47(24):5181–8.
[10] Sundar LS, Sharma KV. Heat transfer enhancements of low volume concentration Al_2O_3 nanofluid and with longitudinal strip inserts in a circular tube. Int J Heat Mass Transfer 2010;53(19-20):4280–6.
[11] Zhou DW. Heat transfer enhancement of copper nanofluid with acoustic cavitation. Int J Heat Mass Transfer 2004;47(14–16):3109–17.
[12] Xuan Y, Li Q. Heat transfer enhancement of nanofluids. Int J Heat Fluid Flow 2000;21(1):58–64.
[13] Sohel MR, Saidur R, Sabri MFM, Kamalisarvestani M, Elias MM, Ijam A. Investigating the heat transfer performance and thermophysical properties of nanofluids in a circular micro-channel. Int Commun Heat Mass Transfer 2013;42(0):75–810.
[14] Mahbubul IM, Fadhilah SA, Saidur R, Leong KY, Amalina MA. Thermophysical properties and heat transfer performance of Al2O3/R-134a nanorefrigerants. Int J Heat Mass Transfer 2013;57(1):100–8.
[15] Sarkar. J. A critical review on convective heat transfer correlations of nanofluids. Renewable Sustainable Energy Rev 2011;15(6):3271–7.
[16] Daungthongsuk W, Wongwises S. A critical review of convective heat transfer of nanofluids. Renewable Sustainable Energy Rev 2007;11(5):797–817.
[17] Mahbubul IM, Saidur R, Amalina MA. Pressure drop characteristics of TiO_2-R123 nanorefrigerant in a circular tube. Eng e-Trans 2011;6(2):124–30.
[18] Peng H, Ding G, Jiang W, Hu H, Gao Y. Measurement and correlation of frictional pressure drop of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube. Int J Refrig 2009;32(7):1756–64.
[19] Firouzfar E, Soltanieh M, Noie SH, Saidi SH. Energy saving in HVAC systems using nanofluid. Appl Therm Eng 2011;31(8–9):1543–5.
[20] Shahrul IM, Mahbubul IM, Saidur R, Sabri MFM, Khaleduzzaman SS. Energy and environmental effects of shell and tube heat exchanger by using nanofluid as a coolant. J Chem Eng Jpn 2014;47(4):340–4.
[21] Shahrul IM, Mahbubul IM, Saidur R, Khaleduzzaman SS, Sabri MFM, Rahman MM. Effectiveness study of a shell and tube heat exchanger operated with nanofluids at different mass flow rates. Numer Heat Transfer, Part A 2013;65 (07):699–713.
[22] Jung J-Y, Cho C, Lee WH, Kang YT. Thermal conductivity measurement and characterization of binary nanofluids. Int J Heat Mass Transfer 2011;54(9-10):1728–33.
[23] Lee S, Choi SUS, Li S, Eastman J. Measuring thermal conductivity of fluids containing oxide nanoparticles. J Heat Transfer 1999;121:2.
[24] Murshed SMS, Leong KC, Yang C. Enhanced thermal conductivity of TiO_2—water based nanofluids. Int J Therm Sci 2005;44(4):367–73.
[25] Eastman J, Choi U, Li S, Thompson L, Lee S. Enhanced thermal conductivity through the development of nanofluids. In: Proceedings of the materials research society symposiumon, Cambridge Univ Press; 1997.
[26] Jung JY, Yoo JY. Thermal conductivity enhancement of nanofluids in conjunction with electrical double layer (EDL). Int J Heat Mass Transfer 2009;52 (1):525–8.
[27] Liu MS, Lin MCC, Tsai C, Wang CC. Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method. Int J Heat Mass Transfer 2006;49(17):3028–33.
[28] Wensel J, Wright B, Thomas D, Douglas W, Mannhalter B, Cross W, Hong H, Kellar J, Smith P, Roy W. Enhanced thermal conductivity by aggregation in heat transfer nanofluids containing metal oxide nanoparticles and carbon nanotubes. Appl Phys Lett 2008;92(2) (023110-0210).
[29] Hwang Y, Ahn Y, Shin H, Lee C, Kim G, Park H, Lee J. Investigation on characteristics of thermal conductivity enhancement of nanofluids. Curr Appl Phys 2006;6(6):1068–71.
[30] Xie H, Wang J, Xi T, Liu Y, Ai F, Wu Q. Thermal conductivity enhancement of suspensions containing nanosized alumina particles. J Appl Phys 2002;91 (7):4568–72.
[31] Choi S, Zhang Z, Yu W, Lockwood F, Grulke E. Anomalous thermal conductivity enhancement in nanotube suspensions. Appl Phys Lett 2001;79(14):2252–4.
[32] Choi SUS, Eastman J. Enhancing thermal conductivity of fluids with nanoparticles. . New York: FED-ASME; 1995; 99–105 (231/MD-vol).
[33] Wright B, Thomas D, Hong H, Groven L, Puszynski J, Duke E, Ye X, Jin S. Magnetic field enhanced thermal conductivity in heat transfer nanofluids containing Ni coated single wall carbon nanotubes. Appl Phys Lett 2007;91 (17):173116.
[34] Das SK, Putra N, Thiesen P, Roetzel W. Temperature dependence of thermal conductivity enhancement for nanofluids. J Heat Transfer 2003;125(4):567–74.
[35] Mahbubul IM, Saidur R, Amalina MA. Influence of particle concentration and temperature on thermal conductivity and viscosity of Al_2O_3/R141b nanorefrigerant. Int Commun Heat Mass Transfer 2013;43:100–4.
[36] Mahbubul IM, Saidur R, Amalina MA. Investigation of viscosity of R123-TiO_2 nanorefrigerant. Int J Mech Mater Eng 2012;7(2):146–51.
[37] Namburu P, Kulkarni D, Misra D, Das D. Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture. Exp Therm Fluid Sci 2007;32(2):397–402.
[38] Nguyen C, Desgranges F, Galanis N, Roy G, Mare T, Boucher S, Anguemintsa H. Viscosity data for Al_2O_3–water nanofluid—hysteresis: is heat transfer enhancement using nanofluids reliable? Int J Therm Sci 2008;47(2):103–11.
[39] Zeinali Heris S, Etemad SGh, Nasr Esfahany M. Experimental investigation of oxide nanofluids laminar flow convective heat transfer. Int Commun Heat Mass Transfer 2006;33(4):529–35.
[40] Murshed S, Leong K, Yang C. Determination of the effective thermal diffusivity of nanofluids by the double hot-wire technique. J Phys D Appl Phys 2006;39 (24):5316.
[41] Veilleux J, Coulombe. S. A total internal reflection fluorescence microscopy study of mass diffusion enhancement in water-based alumina nanofluids. J Appl Phys 2010;108:104316.
[42] Chen H, Ding Y, He Y, Tan C. Rheological behaviour of ethylene glycol based titania nanofluids. Chem Phys Lett 2007;444(4):333–7.
[43] Zhou S-Q, Ni R. Measurement of the specific heat capacity of water-based Al_2O_3 nanofluid. Appl Phys Lett 2008;92(093123):1–3.
[44] Sekhar YR, Sharma KV. Study of viscosity and specific heat capacity characteristics of water-based Al_2O_3 nanofluids at low particle concentrations. J Exp Nanosci 2013:1–17.
[45] Pak BC, Cho YI. Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. Exp Heat Transfer 1998;11(2):151–70.
[46] Xuan Y, Roetzel W. Conceptions for heat transfer correlation of nanofluids. Int J Heat Mass Transfer 2000;43(19):3701–7.
[47] Vajjha RS, Das DK. Specific heat measurement of three nanofluids and development of new correlations. ASME, J Heat Transfer 2009;131(7) 071601–071607.
[48] De Robertis E, Cosme EHH, Neves RS, Kuznetsov AY, Campos APC, Landi SM, Achete CA. Application of the modulated temperature differential scanning calorimetry technique for the determination of the specific heat of copper nanofluids. Appl Therm Eng 2012;41(0):10–7.
[49] Elias MM, Mahbubul IM, Saidur R, Sohel MR, Shahrul IM, Khaleduzzaman SS, Sadeghipour S. Experimental investigation on the thermo-physical properties of Al_2O_3 nanoparticles suspended in car radiator coolant. Int Commun Heat Mass Transfer 2014;54(0):48–53.
[50] Saeedinia M, Akhavan-Behabadi MA, Nasr M. Experimental study on heat transfer and pressure drop of nanofluid flow in a horizontal coiled wire inserted tube under constant heat flux. Exp Therm Fluid Sci 2012;36 (0):158–68.
[51] Saeedinia MA, Akhavan-Behabadi MA, Razi. P. Thermal and rheological characteristics of CuO–Base oil nanofluid flow inside a circular tube. Int Commun Heat Mass Transfer 2012;39(1):152–9.
[52] Shin D, Banerjee D. Enhancement of specific heat capacity of high-temperature silica-nanofluids synthesized in alkali chloride salt eutectics for solar thermal-energy storage applications. Int J Heat Mass Transfer 2011;54(5–6):1064–70.
[53] Fakoor Pakdaman M, Akhavan-Behabadi MA, Razi P. An experimental investigation on thermo-physical properties and overall performance of MWCNT/heat transfer oil nanofluid flow inside vertical helically coiled tubes. Exp Therm Fluid Sci 2012;40(0):103–11.
[54] Choi J, Zhang Y. Numerical simulation of laminar forced convection heat transfer of Al_2O_3–water nanofluid in a pipe with return bend. Int J Therm Sci 2012;55(0):90–102.
[55] Pandey SD, Nema VK. Experimental analysis of heat transfer and friction factor of nanofluid as a coolant in a corrugated plate heat exchanger. Exp Therm Fluid Sci 2012;38(0):248–56.
[56] Chandrasekar M, Suresh S, Senthilkumar T. Mechanisms proposed through experimental investigations on thermophysical properties and forced convective heat transfer characteristics of various nanofluids—a review. Renewable Sustainable Energy Rev 2012;16(6):3917–38.
[57] Teng T-P, Hung Y-H. Estimation and experimental study of the density and specific heat for alumina nanofluid. J Exp Nanosci 2012:1–12.

[58] O'Hanley H, Buongiorno J, McKrell T, Hu L-w. Measurement and model validation of nanofluid specific heat capacity with differential scanning calorimetry. Adv Mech Eng 2012;2012(181079):1–6.
[59] Murshed SMS. Simultaneous measurement of thermal conductivity, thermal diffusivity, and specific heat of nanofluids. Heat Transfer Eng 2011;33 (8):722–31.
[60] Murshed SMS. Determination of effective specific heat of nanofluids. J Exp Nanosci 2011;6(5):539–46.
[61] Kulkarni DP, Vajjha RS, Das DK, Oliva D. Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant. Appl Therm Eng 2008;28(14-15):1774–81.
[62] Nieh H-M, Teng T-P, Yu C-C. Enhanced heat dissipation of a radiator using oxide nano-coolant. Int J Therm Sci 2014;77(0):252–61.
[63] Sonawane S, Patankar K, Fogla A, Puranik B, Bhandarkar U, Sunil Kumar S. An experimental investigation of thermo-physical properties and heat transfer performance of Al_2O_3-aviation turbine fuel nanofluids. Appl Therm Eng 2011;31(14–15):2841–9.
[64] Starace Anne K, Gomez Judith C, Wang Jun, Pradhan Sulolit, Glatzmaier GC, Greg C. Nanofluidheatcapacities. J Appl Phys 2011;110(124323):1–5.
[65] Lee J, Mudawar I. Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels. Int J Heat Mass Transfer 2007;50(3):452–63.
[66] Ho MX, Pan C. Optimal concentration of alumina nanoparticles in molten Hitec salt to maximize its specific heat capacity. Int J Heat Mass Transfer 2014;70(0):174–84.
[67] Shin D, Banerjee D. Specific heat of nanofluids synthesized by dispersing alumina nanoparticles in alkali salt eutectic. Int J Heat Mass Transfer 2014;74:210–4.
[68] Shin D, Banerjee D. Enhanced specific heat of silica nanofluid. J Heat Transfer 2010;133(2) (024501-024501).
[69] Shin D, Banerjee D. Effects of silica nanoparticles on enhancing the specific heat capacity of carbonate salt eutectic (work in progress). Int J Struct Change Solids 2010;2(2):25–31.
[70] Namburu PK, Kulkarni DP, Dandekar A, Das DK. Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids. Micro Nano Lett IET 2007;2(3):67–71.
[71] Mohebbi A. Prediction of specific heat and thermal conductivity of nanofluids by a combined equilibrium and non-equilibrium molecular dynamics simulation. J Mol Liq 2012;175(0):51–8.
[72] Zhou L-P, Wang B-X, Peng X-F, Du X-Z, Yang Y-P. On the specific heat capacity of CuO nanofluid. Adv Mech Eng 2010;2010(172085):1–4.
[73] Pantzali MN, Kanaris AG, Antoniadis KD, Mouza AA, Paras SV. Effect of nanofluids on the performance of a miniature plate heat exchanger with modulated surface. Int J Heat Fluid Flow 2009;30(4):691–9.
[74] Teng T-P, Yu C-C. Heat dissipation performance of MWCNTs nano-coolant for vehicle. Exp Therm Fluid Sci 2013;49(0):22–30.
[75] Kumaresan V, Velraj R. Experimental investigation of the thermo-physical properties of water–ethylene glycol mixture based CNT nanofluids. Thermochim Acta 2012;545(0):180–6.
[76] Nieto de Castro CA, Murshed SMS, Lourenço MJV, Santos FJV, Lopes MLM, França JMP. Enhanced thermal conductivity and specific heat capacity of carbon nanotubes ionanofluids. Int J Therm Sci 2012;62(0):34–9.
[77] Liu J, Wang F, Zhang L, Fang X, Zhang Z. Thermodynamic properties and thermal stability of ionic liquid-based nanofluids containing graphene as advanced heat transfer fluids for medium-to-high-temperature applications. Renewable Energy 2014;63(0):519–23.
[78] A. Ghozatloo, A. Rashidi, M. Shariaty-Niassar. Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger. Exp Therm Fluid Sci 2013.
[79] He Q, Wang S, Tong M, Liu Y. Experimental study on thermophysical properties of nanofluids as phase-change material (PCM) in low temperature cool storage. Energy Convers Manage 2012;64(0):199–205.
[80] Nelson IC, Banerjee D, Ponnappan. R. Flow loop experiments using polyalphaolefin nanofluids. J Thermophys Heat Transfer 2009;23(4):752–61.
[81] Ghazvini M, Akhavan-Behabadi MA, Rasouli E, Raisee M. Heat transfer properties of nanodiamond-engine oil nanofluid in laminar flow. Heat Transfer Eng 2011;33(6):525–32.
[82] Saidur R, Leong KY, Mohammad. HA. A review on applications and challenges of nanofluids. Renewable Sustainable Energy Rev 2011;15(3):1646–68.
[83] Saidur R, Kazi SN, Hossain MS, Rahman MM, Mohammed HA. A review on the performance of nanoparticles suspended with refrigerants and lubricating oils in refrigeration systems. Renewable Sustainable Energy Rev 2011;15 (1):310–23.
[84] Mahbubul IM, Saidur R, Amalina MA. Latest developments on the viscosity of nanofluids. Int J Heat Mass Transfer 2012;55(4):874–85.
[85] Tanvir S, Qiao L. Surface tension of nanofluid-type fuels containing suspended nanomaterials. Nanoscale Res Lett 2012;7(1):1–10.
[86] Chen R-H, Phuoc TX, Martello D. Surface tension of evaporating nanofluid droplets. Int J Heat Mass Transfer 2011;54(11–12):2459–66.
[87] Ijam A, Saidur R. Nanofluid as a coolant for electronic devices (cooling of electronic devices). Appl Therm Eng 2012;32(0):76–82.
[88] Ijam A, Saidur R, Ganesan P. Cooling of minichannel heat sink using nanofluids. Int Commun Heat Mass Transfer 2012;39(8):1188–94.
[89] Strandberg R, Das DK. Influence of temperature and properties variation on nanofluids in building heating. Energy Convers Manage 2010;51(7):1381–90.
[90] Bergman TL. Effect of reduced specific heats of nanofluids on single phase, laminar internal forced convection. Int J Heat Mass Transfer 2009;52(5–6):1240–4.
[91] Vanapalli S, ter Brake H. Assessment of thermal conductivity, viscosity and specific heat of nanofluids in single phase laminar internal forced convection. Int J Heat Mass Transfer 2013;64:689–93.
[92] Wang B-X, Zhou L-P, Peng X-F. Surface and size effects on the specific heat capacity of nanoparticles. Int J Thermophys 2006;27(1):139–51.
[93] Gangacharyulu D. Preparation and characterization of nanofluids and some investigation in biological applications. In: Mechanical engineering. Carbondale: Southern Illinois University; 104.